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FIVE YEARS OF EXPERIMENTAL TESTING WITH A 1.5 KILOWATT WIND TURBINE

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ABSTRACT

A 1.5 kW wind turbine has been continuously tested since 1992 at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX, for pumping water for domestic and livestock use. This wind turbine used a permanent magnet alternator that provided variable-voltage, variable-frequency, 3-phase AC electricity which powered off-the-shelf submersible motors and centrifugal pumps without the use of an inverter. Data that have been collected for the past five years include: flow rate, wind speed, pressure(simulated pumping depth), voltage, current, frequency, and electrical power. Data were collected for four different pumps at pumping depths ranging from 20 m to 100 m. The optimum pump was found to be a function of the water well depth and the wind speed distribution. A chronological history of significant events and failures is also documented in the paper. This wind turbine had an availability of 93% over the past five years. The individual contributions to downtime were: problems with the wind turbine/controller (5%), icing of the blades (1%), problems with the motor/pump (1/2%), and miscellaneous (1/2%). After correcting initial start-up problems, the 1.5 kW wind turbine proved very reliable over the past five years.

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INTRODUCTION

Wind-electric water pumping systems have been tested at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX since 1988. Several papers have been written on the performance and economic feasibility of wind-electric systems compared to windmills[1,2], solar water pumping systems[3], and to utility powered submersible motors and pumps[4]. One of the most successful wind-electric water pumping systems is the Bergey Windpower† 1500-PD(see Table 1). The Bergey 1500 is rated at 1.5 kW at a wind speed of 12.5 m/s. The generator is a permanent magnet alternator (PMA) which generates variable-voltage, variable-frequency 3ϕ AC electricity which can power off-the-shelf submersible motors without the need of an inverter. An inverter is not needed as long as a certain amount of capacitance is added in parallel with the inductive motor (i.e. for power factor improvement). Water pumping performance for the Bergey 1500-PD has been previously published for 30 m to 50 m pumping depths for three different pumps[5]. Bergey 1500-PD pumping performance is documented in this paper for four different pumps at pumping depths ranging from 20 m to 100 m. The Bergey 1500-PD has been very reliable for pumping water and reliability is as important to a farmer or rancher as the cost and performance of the water pumping system.

†The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

HISTORY OF TESTING ON BERGEY 1500-PD

Table 2 shows a chronological history of the testing done on the Bergey 1500-PD by the USDA-ARS Conservation and Production Research Laboratory near Bushland, TX(located 16 km west of Amarillo, TX). Several stators in the PMA shorted out during the first year of testing. This problem was corrected when new wiring was laid underground between the wind turbine and the controller -- the previous underground electrical cable was an extension of an old pump motor line. The stator that was installed in 5/7/92 is still operating today -- over five years later. On 4/5/93 the high frequency cut-out was changed from 90 Hz to 75 Hz. This was significant because prior to this numerous downtimes occurred due to thermal cut-outs (current above setpoint). The controller has a thermal cut-out circuit to protect the motor and the stator from receiving too much current. The thermal relay is adjustable from 5 to 8 A. With the thermal cut-out set at 8 A and the high frequency cut-out set to 75 Hz, the thermal relay was seldom triggered. There is also a manual and automatic setting on the thermal relay. If set to manual, the wind turbine will stay offline until manually reset by an operator. If it is in the automatic mode, the relay will stay off until the bimetalic strip in the relay has cooled down whereupon the controller will automaticly begin cutting the wind turbine back in again.

Sometime during the first two years of testing the capacitance/phase was switched from 60 μF to 30 μF. This non-optimum capacitance (30 μF) was not increased until 3/29/94. On 3/29/94, the high frequency cut-out was also increased to 78 Hz to keep the turbine online more of the time at higher wind speeds. Occasionally (about once a year) some of the wires to the capacitors would burn completely through which had the effect of lowering the capacitance. The problem was caused by a loose connection of spade connectors on the capacitors, and soldering the wires directly to the capacitors will eliminate this problem. On 4/13/96 the submersible motor failed. The submersible motor had operated for about four years before the failure. On 5/27/96 two blade failures occurred due to striking the tower. The reason for the blades striking the tower was due to the metal flanges on the magnet can (where the blades were attached) being bent inward toward the tower. During the four years of continuous testing prior to the failure, the force of the wind against the blades had slowly bent the flanges in toward the tower. The manufacturer had already identified this problem and had doubled the thickness of steel flanges on its new PMAs. Also in 1996, one of the pumps began operating inefficiently after having been tested for about 2.5 years. The pump would tend to stick in a certain position and needed a high wind speed (e.g. high current) to get it unstuck. This pump had no problem running on the utility because if it ever got stuck then the utility could supply enough current to get it unstuck.

In summation, the only design deficiency (steel flanges on PMA being too thin) determined over five years of testing on this wind turbine has been corrected by the wind turbine manufacturer. Downtime is still experienced on this turbine due to blown fuses in the controller -- mainly in the battery charging circuit. The manufacturer is currently designing a new pump controller which should significantly decrease or eliminate the downtimes completely. While there was one motor failure and one pump failure during testing -- the failures occurred after years of continuous testing.

EXPERIMENTAL SET UP

The experimental set up at the USDA-ARS Laboratory in Bushland, TX is shown in Figure 1. For calibration of instrumentation and trouble-shooting, a double-throw switch was installed to allow electricity to be supplied from either the utility or the wind turbine. Water was pumped from and discharged back into an underground sump. A pressure regulator valve was used to set the pressure in the pumping system to simulate different pumping heads. The back pressure tank was used to steady the pressure in the pumping system.

Variables which were measured in the experimental set up included:

1. Time (Day, Hour., Minutes)
2. Wind turbine hub height wind speed (m/s)
3. Electrical frequency (Hz)
4. Voltage (V)
5. Current (A)
6. Water Pressure (kPa)
7. Flow rate (l/min)
8. Wind turbine power (kW).

When these variables were measured, samples were collected each second, and the average value was recorded on a storage module via a Campbell† 21x data logger. The data collected was processed using a "C++" program which binned the data in 0.5 m/s increments and graphed the variables on the computer as a function of wind speed. The data was processed daily (Monday through Friday except on holidays) in order to identify and correct any problems in instrumentation or the wind-electric system.

BERGEY 1500-PD PUMPING PERFORMANCE

The submersible motors and pumps used with the Bergey 1500-PD are off-the-shelf, meaning they are mass produced (cheap) and can be obtained virtually anywhere in the world. When determining the proper wind-electric water pumping system, the submersible motor is sized according to the generator power rating. Usually the optimum motor for water pumping will have a power rating one-half to two-thirds the rated power of the wind turbine. The optimum motor determined by Bergey Windpower was a 230 V 3ϕ AC 1.1 kW Franklin Electric† submersible motor. The pumps recommended by Bergey Windpower were to have a 0.75 kW power rating. As the pumping depth increases, pumps with more stages should be selected. The pumps recommended by Bergey Windpower are Grundfos† pumps, so an explaination of the Grundfos model designation is necessary. The Grundfos model designation is xxSyy-zz which means the following:

xx-the flow rate that this pump is rated at in gallons/minute

yy-the power in horsepower after being multiplied by 10(e.g. "10" means 1hp)

zz-the number of stages in the pump.

Figures 2-5 show the flow rate as a function of wind speed for the different pumps tested on the Bergey 1500-PD. While the lower staged pumps in Figures 2 and 3 have higher maximum flow rates, the higher staged pumps in Figures 4 and 5 have lower cut-in wind speeds and can pump water from deeper depths. The system efficiencies of all these pumps are shown in Figures 6-9. The definition of system efficiency is the amount of power required to pump the water to the surface divided by the power in the wind passing through the rotor disc of the wind turbine. While the flow rate is somewhat dependent on the altitude and the air temperature, the system efficiency is independent of the altitude and air temperature. Although the air density was not collected on this data acquisition system, it was collected on another data acquisition system, and that data was used to estimate the system efficiency. As the number of stages of the pump increases, the maximum system efficiency occurs at a deeper pumping depth. The system efficiency is a combination of the efficiency of the wind turbine to convert the wind energy into electrical power and the efficiency of the motor/pump to convert the electrical power back to mechanical power for pumping water.

Figure 10 shows the power curve measured for one of the motor/pump combinations and the power coefficient. It is interesting to note that the power measured at a wind speed of 12.5 m/s is about 1500 W -- same as that specified by the manufacturer. Since the average air density for this data is 1.029 kg/m^3, the power of this wind turbine should be about 20% higher at sea level/standard day conditions. The power curve drops off at 14.5 m/s due to the wind turbine exceeding its frequency cut-out and furling. The power coefficient (Figure 10) remains relatively constant over a wind speed range of 7 to 12 m/s. This constant power coefficient is due to the rotor rpm increasing with wind speed which maintains a constant angle-of-attack of the relative wind to the blade. The maximum power coefficient is about 0.23 which means 23% of the wind energy is converted to electrical power. The pump efficiency is also determined for this particular pump at a 60 m head (Figure 11). The maximum pump efficiency (39%) is not achieved until a wind speed of 10 m/s is reached. Since the frequency is usually 60 Hz and the voltage is 230 V at this wind speed, this condition is equivalent to that of utility supplied electricity (in the USA) which is probably why the pump efficiency reaches a maximum at this wind speed. Grundfos pump curves are shown in Figure 12, and they are used for someone selecting a pump who is using utility supplied electricity. Since the power generated by the wind turbine is not similar to the power generated by the utility, these pump curves supplied by the manufacturer should not be used for selecting the proper pump. In order to determine the proper pump for a wind-electric system, the wind resource and the pumping depth has to be estimated. Weibull probability distributions are usually used to categorize the wind resource. Below is the equation for the Weibull probability distribution for a wind velocity u.

$$P(u)=\{k/c(u/c)^{k-1}\exp[-(u/c)^{k}]\}\Delta u \qquad (1)$$

The Weibull probability distribution depends mainly on the average wind speed (V_{avg}) and k (a shape factor). A higher k means less variability in the wind speed, and a lower k means more variability in the wind speed. For most of the United States, k varies between 1.8 and 2.4[6]. "c" is a scale factor which can be represented[7] by the following equation:

$$c=V_{avg}\,/\,\Gamma(1+1/k)=V_{avg}/0.89 \qquad (2)$$

Figure 13 shows the monthly average wind speeds and k parameters measured at a height of 10 m in Bushland, TX from 1983 to 1996. Using Bushland's average monthly wind distributions and the flow rate curves in Figures 2-5, daily water volumes were calculated for each of the pumps at constant heads (Figures 14-18). The optimum pump for the 20 m head is the 25S10-7 pump. For the 40 m head, the 16S10-10 pumps the most water. The 10S10-15 pumps the most water at a 60 m head. For 80 and 100 m heads, the 7S10-19 appears to be the optimum pump. Since wind distributions vary from place to place, it may be interesting to determine the optimum pump for four very different wind distributions. The wind distributions chosen for analysis are shown in Figure 19, and they are Weibull distributions with the following parameters:

1. V_{avg}=4 m/s & k=2
2. V_{avg}=4 m/s & k=3
3. V_{avg}=7 m/s & k=2
4. V_{avg}=7 m/s & k=3

Figure 20 shows the optimum pump for an average wind speed of 4 m/s and two k values, 2 and 3. It is obvious that daily water volume and pump selection is very dependent on the k value at this wind speed. Figure 21 shows the optimum pump for the same k values as Figure 20, but at a much higher average wind speed (7 m/s). At this wind speed, daily water volume and pump selection is fairly independent of the k value.

CONCLUSIONS

The reliability and water pumping performance of a 1.5 kW (Bergey 1500-PD) wind-electric water pumping system was evaluated in this paper. After some initial start-up problems were corrected in the first year of testing, the Bergey 1500-PD has operated almost continuously since May of 1992 (5.5 years to date). The only downtime that occurred due to the wind turbine was caused by a design flaw which has since been corrected by the manufacturer. Most of the other downtime that occurred was due to the controller. Much of this downtime has been eliminated by selecting the proper settings for the controller. There still is downtime on this system due to the controller, but the manufacturer is currently designing a new controller to eliminate the problem and reduce the cost. Although there was one motor failure and one pump failure, both operated years before failures. The maximum power coefficient measured on this wind turbine was 0.23, and the power coefficient remained fairly constant over a broad wind speed range. The system efficiency for all the pumps at various pumping depths was measured. The maximum system efficiency occurred at deeper pumping depths as the number of stages on the pump increased. The optimum pump for a wind-electric system was found to be dependent on the pumping depth and the wind resource. Some charts are shown in the paper for selecting the optimum pump for four very different Weibull distributions. From these charts, it appears that the k value of the Weibull distribution is very important in the selection of the optimum pump at low wind speeds, but not very important at high wind speeds.

ACKNOWLEDGEMENTS

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Table 1. Bergey Windpower 1500-PD Specifications

Performance	
Start-Up Wind Speed	3.6 m/s
Cut-In Wind Speed	Variable
Rated Wind Speed	12.5 m/s
Furling Wind Speed(no Load)	13.4 m/s
Maximum Design Wind Speed	54 m/s
Rated Power	1500 W
Rotor Speed	100-500 RPM
Mechanical	
Type	3 Blade Upwind
Rotor Diameter	3.05 m
Chord	11.25 cm
Twist	Varies with RPM due to pitch weight
Pitch	8 deg
Weight	76 kg
Overspeed Control	Horizontal Furling
Gearbox/Belts	None, Direct Drive
Electrical	
Output Waveform	Variable-Voltage Variable-Frequency 3ϕ AC
Generator	Permanent Magnet Alternator

Table 2. Chronological History of Bergey 1500-PD

Date	Activity
4/5/91	Installed wind turbine with crane.
4/29/91	Instrumentation and wiring completed. Turbine online.
5/16/91	Stator in wind turbine permanent magnet alternator(PMA) shorted. Turbine down.
8/27/91	Installed second stator. Turbine back online.
10/18/91	Second stator shorted. Turbine down.
4/16/92	Installed third stator. Turbine back online.
4/20/92	Third stator shorted. Turbine down.
4/30/92	Installed new wiring in 2.54 cm PVC pipe underground between wind turbine and controller.
5/7/92	Installed fourth stator. Turbine back online.
6/2/92	Tower base and lower tower section bent (vehicle accident). Turbine off.
6/9/92	Used crane to replace tower base and lower tower section. Turbine online.
4/5/93	Changed high frequency cut-out from 90 to 75 Hz.
3/29/94	Changed capacitance/phase from 30 to 60 μF, also increased high freq. cut-out from 75 to 78 Hz.
10/2/95	Set thermal trip from manual to automatic.
11/10/95	Circuit board on controller burned during high wind speeds (>20 m/s). System off.
11/21/95	Installed new circuit board. System online.
4/13/96	Submersible motor failure. System off.
4/17/96	Installed new motor. System online.
5/27/96	Two blade failures, tower damaged. Turbine down.
6/13/96	Replaced: magnet can of PMA, 3 blades, yaw bearing, tower top section. Turbine back online.
9/25/96	Replaced pump because had trouble sometimes starting in wind speeds below 10 m/s.

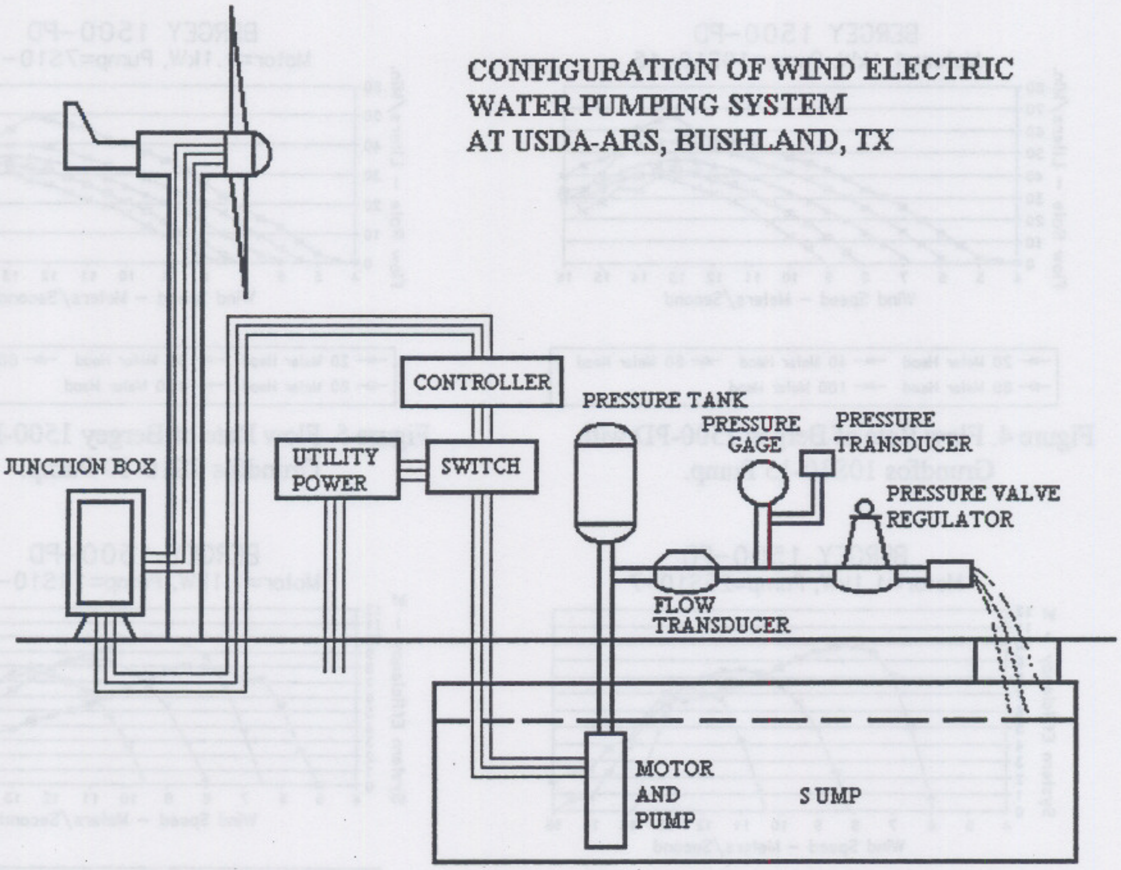

Figure 1. Schematic of Wind-Electric Water Pumping System at the USDA-ARS, Bushland, TX.

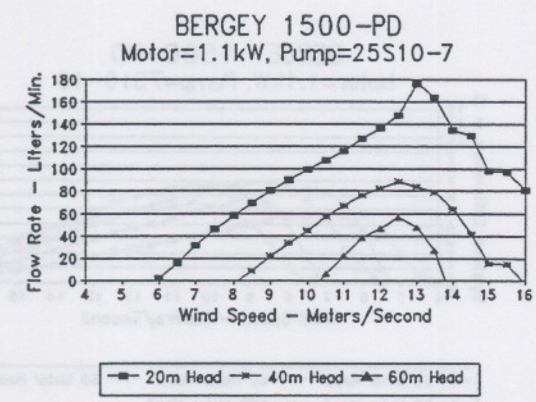

Figure 2. Flow Rate of Bergey 1500-PD with Grundfos 25S10-7 Pump.

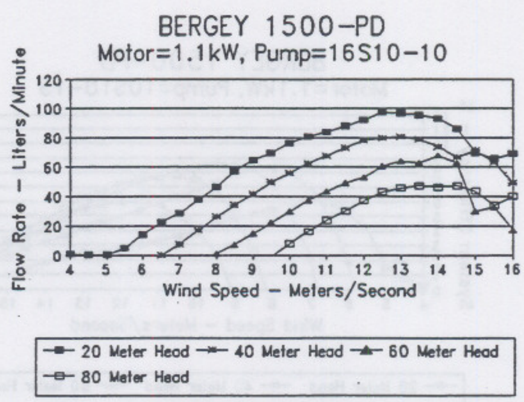

Figure 3. Flow Rate of Bergey 1500-PD with Grundfos 16S10-10 Pump.

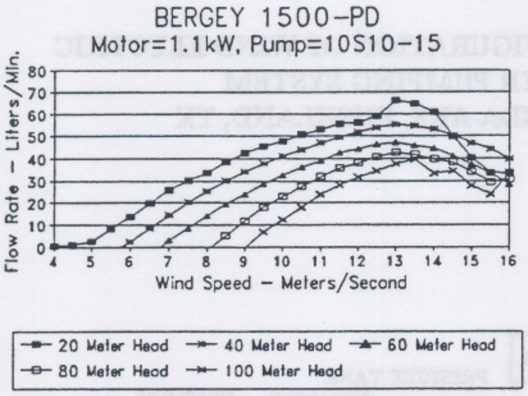

Figure 4. Flow Rate of Bergey 1500-PD with Grundfos 10S10-15 Pump.

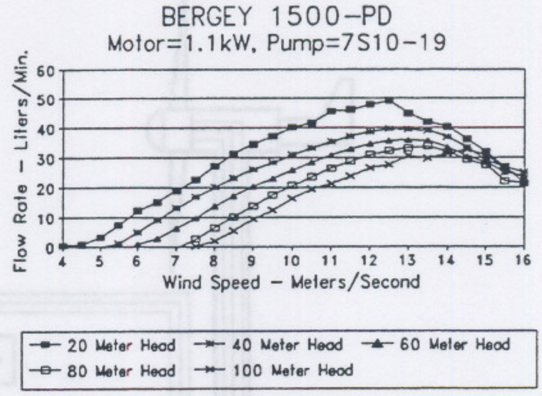

Figure 5. Flow Rate of Bergey 1500-PD with Grundfos 7S10-19 Pump.

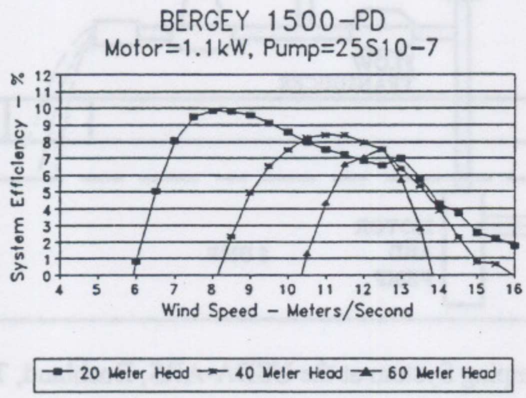

Figure 6. System Efficiency of Bergey 1500-PD with Grundfos 25S10-7 Pump.

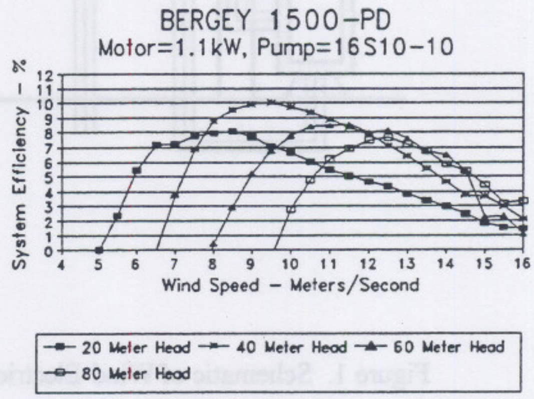

Figure 7. System Efficiency of Bergey 1500-PD with Grundfos 16S10-10 Pump.

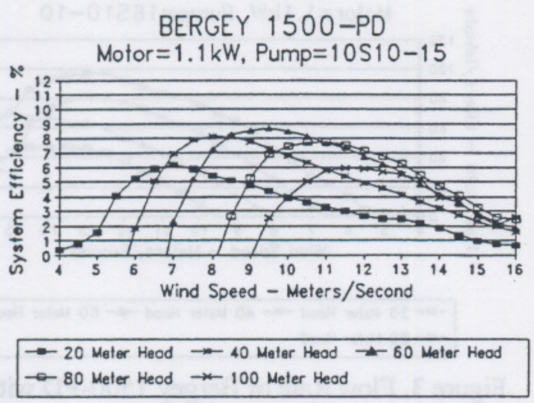

Figure 8. System Efficiency of Bergey 1500-PD with Grundfos 10S10-15 Pump.

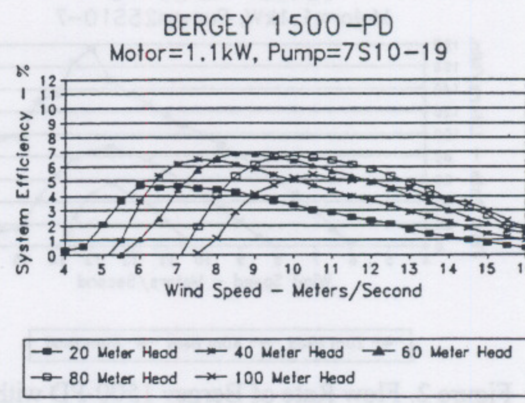

Figure 9. System Efficiency of Bergey 1500-PD with Grundfos 7S10-19 Pump.

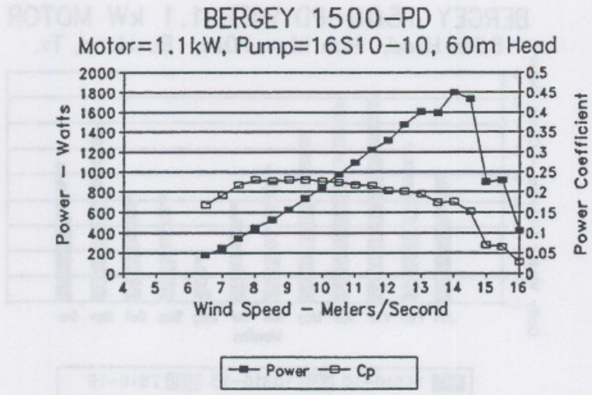

Figure 10. Power and Power Coefficient of Bergey 1500-PD with Grundfos 16S10-10 Pump

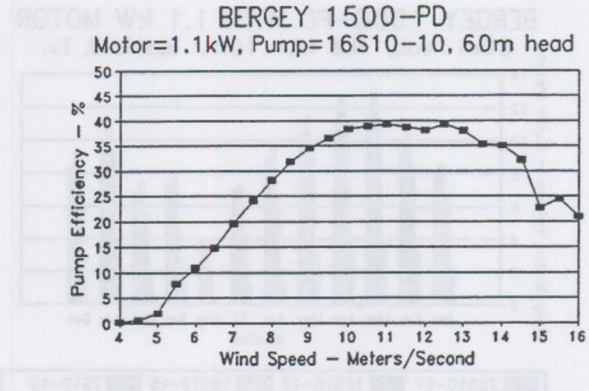

Figure 11. Pump Efficiency of Bergey 1500-PD with Grundfos 16S10-10 Pump.

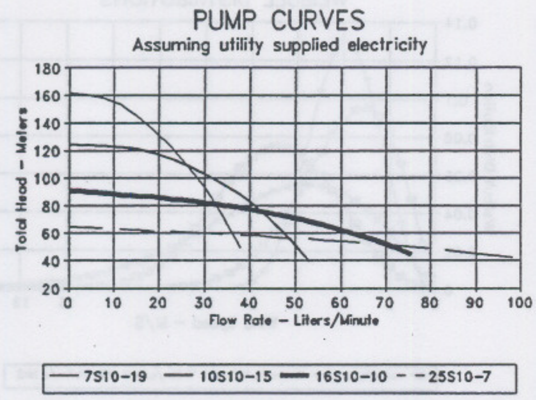

Figure 12. Grundfos published pump curves for pumps tested on Bergey 1500-PD.

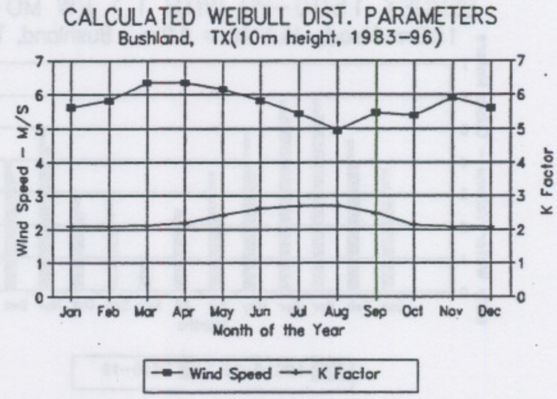

Figure 13. Calculated Weibull probability distribution parameters for Bushland, TX.

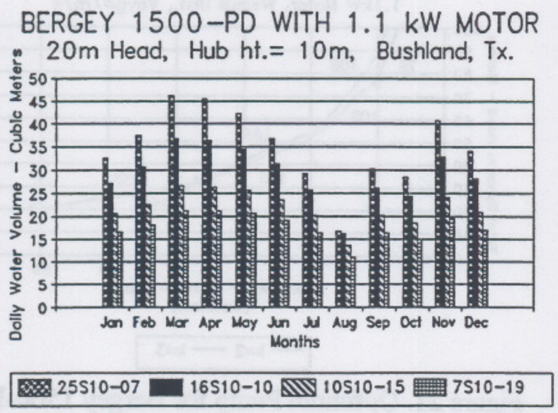

Figure 14. Daily Water Volume of Bergey 1500-PD at a 20 m head for Different Pumps.

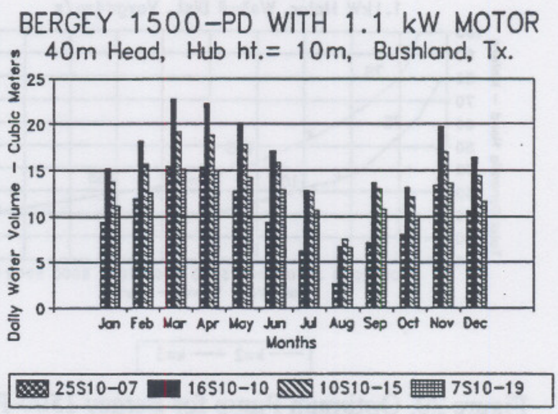

Figure 15. Daily Water Volume of Bergey 1500-PD at a 40 m head for Different Pumps.

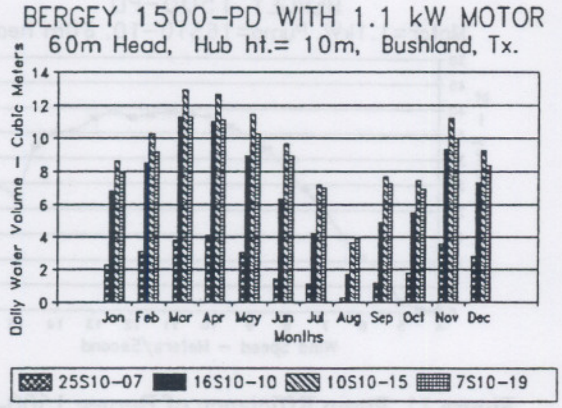

Figure 16. Daily Water Volume of Bergey 1500-PD at a 60 m head for Different Pumps.

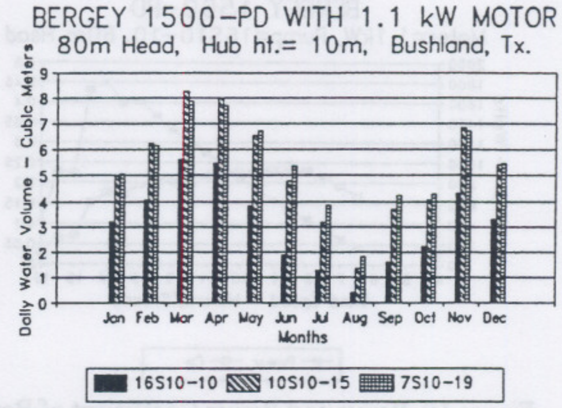

Figure 17. Daily Water Volume of Bergey 1500-PD at a 80 m head for Different Pumps.

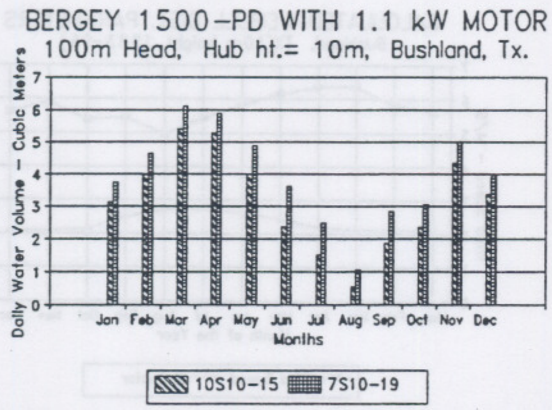

Figure 18. Daily Water Volume of Bergey 1500-PD at a 100 m head for Different Pumps.

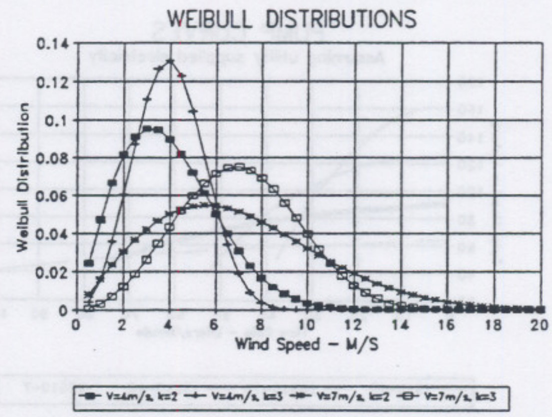

Figure 19. Four Different Weibull distributions with two different wind speeds and k factors.

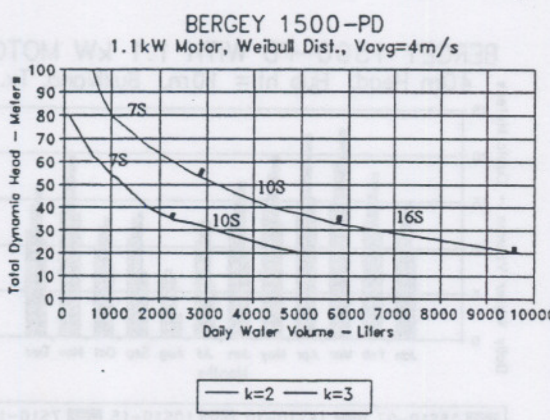

Figure 20. Optimum Pump for Bergey 1500-PD with Weibull Dist.(Vavg= 4m/s, k=2&3).

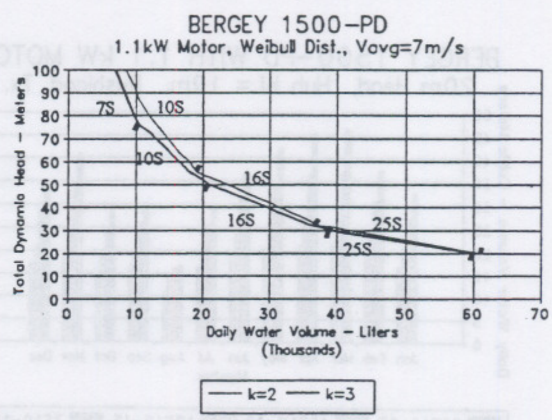

Figure 21. Optimum Pump for Bergey 1500-PD with Weibull Dist.(Vavg= 7m/s, k=2&3).